Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 161 (2016) 332 – 336

Procedia Engineering

www.elsevier.com/locate/procedia

World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016

Seismic Assessment of Reinforced Concrete Frameworks Through Advanced Pushover Analysis and Nonlinear Response of A SDOF Oscillator

Szabolcs Varga[a,*], Cosmin G. Chiorean[a]

[a]*Faculty of Civil Engineering, Technical University of Cluj-Napoca, 15 C. Daicoviciu Str., RO-400020 Cluj-Napoca, Romania*

Abstract

This paper presents an integrated system for advanced structural analysis and seismic performance evaluation of 2D reinforced concrete frameworks. The advanced non-linear inelastic static analysis employed herein uses the accuracy of the fibre elements approach for large deflection inelastic frame analysis and address its efficiency and modelling shortcomings both to element level, through the use of only one element to model each physical member of the frame, and to cross-sectional level through the use of path integral approach for numerical integration of the cross-sectional nonlinear characteristics. Evaluation of the seismic performance is achieved with an approach that uses nonlinear time-history analysis (NTHA) of a single degree-of-freedom (SDOF) oscillator. The inelastic ductility and displacement demand is determined directly from accelerograms, without graphical or numerical approximations. Several computational examples are given to validate the effectiveness of the proposed method, the reliability and time saving of the code. The influence of the accuracy of the second-order nonlinear inelastic analysis methods involved in the modelling of the selected RC frame in conjunction with the distributions of the pushover lateral loads is pointed out. The proposed procedure is developed in the framework of Eurocode 8 design methodology, as reliable tool ready to be implemented into everyday design practice for advanced analysis, pushover analysis, and seismic performance evaluation of RC frame structures.

Peer-review under responsibility of the organizing committee of WMCAUS 2016

Keywords: advanced analysis; pushover analysis; ductility demand; target displacement; Eurocode 8;

* Corresponding author. Tel.: +40 740842810.
E-mail address: szabolcs.varga@mecon.utcluj.ro

Peer-review under responsibility of the organizing committee of WMCAUS 2016
doi:10.1016/j.proeng.2016.08.568

1. Introduction

Since Kobe and Northridge earthquakes, nonlinear static analysis (pushover analysis), became an accepted method for the seismic evaluation of structures. [1][4][8]. In spite of the availability of some FEM algorithms and powerful computer programs, the non-linear inelastic analysis of real large-scale frame structures still possesses huge demands on the most powerful of available computers and still represents unpractical tasks to most designers. Recently, more reliable nonlinear inelastic analysis techniques were published, which are essential in performance-based earthquake engineering and advanced analysis methodologies. [5], [2],[11]. Nonlinear inelastic analysis employed herein uses the accuracy of the fibre elements approach for inelastic frame analysis and addresses its efficiency and modelling shortcomings both to element level, through the use of only one element to model each physical member of the frame, and to cross-sectional level through the use of path integral approach to numerical integration of the cross-sectional nonlinear characteristics. This is an essential requirement to approach real large spatial frame structures, combining modelling benefits, computational efficiency and reasonable accuracy. The proposed method combines the determination of capacity curves through advanced nonlinear inelastic analysis (pushover), while target displacements are determined using NTHA of a SDOF oscillator. In addition, present work aims to emphasize the role of the accurate modelling and pushover analysis lateral load distributions in the determination of the capacity curve, the determination of target displacements and interstory drifts.

2. Proposed method for advanced nonlinear inelastic analysis of RC frameworks

2.1. Advanced nonlinear inelastic analysis

The following assumptions are often adopted in the formulation of realistic analytical model: (1) Plane section remain plane after flexural deformation; (2) Full strain compatibility exists between concrete and steel reinforcement; (3) Reinforcement steel bars cannot buckle under compression; (4) Mechanical properties of concrete may vary according to confinement levels. Flexibility-based method is used to formulate the distributed plasticity model of a 2D frame element (6 DOF) under the above assumptions where elasto-plastic behaviour is modelled accounting for spread-of plasticity effect in sections and along the element and employs modelling of structures with only one-line element per member, which reduces the number of degree of freedom involved and the computational time. The first two assumptions allow the formulation details to be considered on two distinct levels, namely, the cross-sectional level and the member longitudinal axis level. Thus the nonlinear response of a beam-column element can be computed as a weighted sum of the response of a discrete number of cross-sections. In the present elasto-plastic frame analysis approach, gradual plasticization through the cross-section subjected to combined action of axial force and bending moment is described through basic equilibrium, compatibility and material nonlinear constitutive equations σ-ε of concrete and reinforcement steel, in any section by an iterative process. In this way the arbitrary cross-sectional shape and reinforcement layout the effect of concrete tensile cracking, the nonlinear compressive response of concrete with different levels of confinement are accurately included in the analysis. Using an updated Lagrangian formulation (UL) the nonlinear geometrical effects are considered updating the element forces and geometry configurations at each load increment. In order to trace the equilibrium path, for proportionally and non-proportionally applied loads, the proposed model has been implemented in an incremental-iterative matrix structural-analysis computer program, Nefcad, and the full procedure has been described extensively in [6] and [14]

2.2. Determination of target displacements

The method used hereinafter for determination of target displacements involves the determination of the capacity curve by means of an advanced pushover analysis (described in chapter 2.1), as well as determination of the ductility demand, directly computed using the behaviour of an SDOF oscillator with strength R_μ equal to that of the equivalent SDOF structural system. The transformation of the capacity curve of the MDOF (pushover curve) system into the bilinear capacity diagram of the SDOF system is implemented via the principles of the well-known N2 method (Eurocode 8) [4] [7] The characteristics of the equivalent SDOF: period T^*, yield force F^*_y, yield and ultimate displacements D^*_y, D^*_u are computed. R_μ elastic accelerations reduction factor determined, and it is the ratio between the elastic acceleration $S_{ae}(T^*)$, and the yield capacity S_{ay} expressed in accelerations of the bi-linearized equivalent SDOF system. At this point, proposed target displacement procedure differs from N2 method, as described below. From conceptual point of view, the proposed method is thus similar to the ”Yield Point Spectra” method (YPS) [3], except that it allows the identification of the μ ductility demand from the intrinsic characteristics of the seismic record and those of the equivalent SDOF system. This feature of the proposed approach could eliminate the necessity to use empirical relationships like in the case of the traditional design code NSA methods (e.g. N2 method). For the full description of the determination of the target displacements using the proposed method reader is referred to [14]

3. Case study

3.1. Structure and modelling

The structure analysed in present case study was previously assessed in [9]. The geometry of the frame, cross-sectional and material characteristics are shown in Fig.1, uniform distributed loads of 20kN/m was applied to the beam elements. In the referenced article, nonlinear static and dynamic analyses have been performed using the software OpenSees [13], the characteristics of nonlinear modelling has been described in [9]. The authors aimed to reproduce the same modelling in Seismostruct [12] and Nefcad [6] advanced nonlinear analysis software. In the process of validating the proposed method, 8 accelerograms were matched to the design spectrum with NCR=100 years, PGA=0.24g, and corner period Tc=1.6s, using the earthquake records taken in Bucharest at the 1977 and 1986 earthquakes. The inelastic spectra were developed using Bispec software, [10].

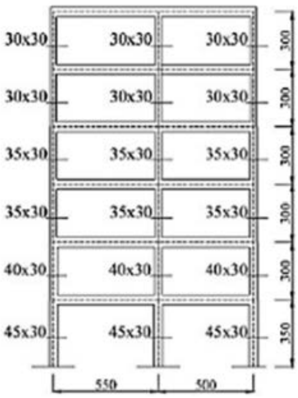

Figure 1a) The geometrical configuration of the analyses structure.

Level	Column reinforcement
1	6Φ16
2	6Φ16
3	4Φ16
4	4Φ16
5	4Φ16
6	4Φ16

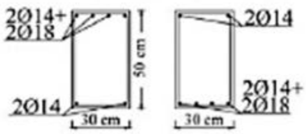

Figure 1b) Beam and column reinforcement.

$f_y = 414 \cdot MPa$

$E_s = 210000\ MPa$

$\frac{E_s}{E_i} = 0.009$

$f_{co} = 33 \cdot MPa$

$\varepsilon_{co} = 0.0022$

$\varepsilon_{cu} = 0.0035$

Figure 1c) Material characteristics.

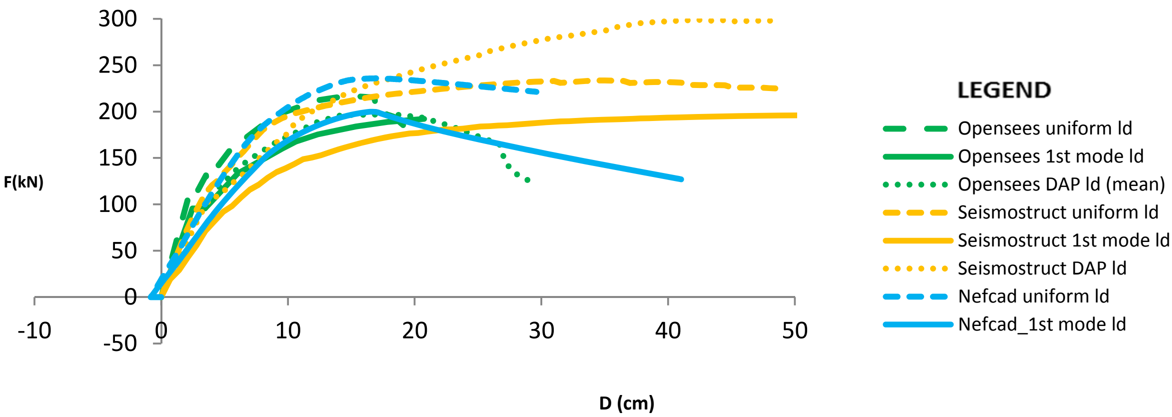

Fig. 2. Pushover curves from Opensees [9] plotted against pushover curves obtained from Seismostruct and proposed Nefcad software.

3.1. Upper story displacements

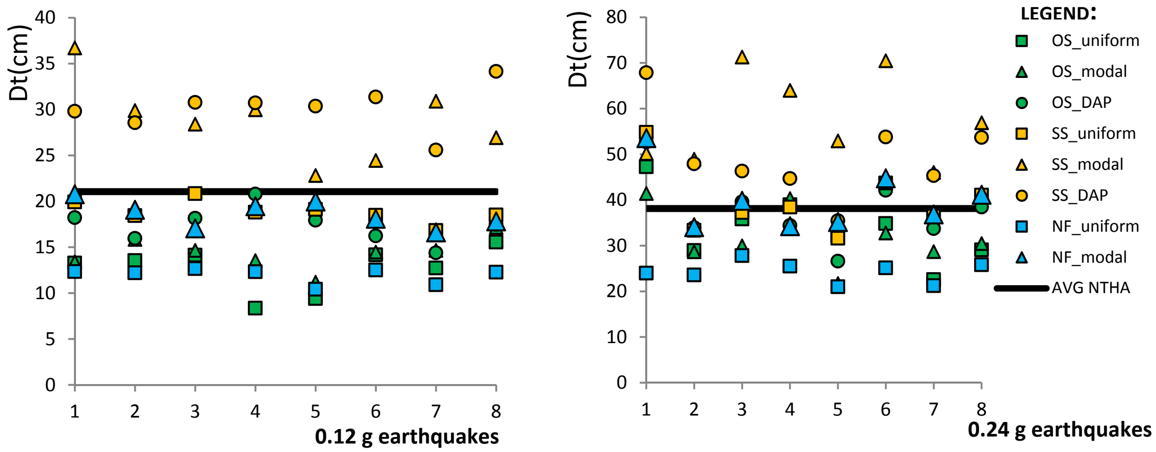

Fig.3.Displacement demands for proposed method and average value of NTHA-s for 0,12 g and 0.24 g earthquake.

Target displacements were determined using proposed method, for the set of 0.12g and 0.24g earthquakes, in order to highlight the influence of each of the three types of structural analysis (Opensees, Seismostruct, and Nefcad), modelling, and lateral load distributions (LLD). The effectiveness of the proposed advanced pushover analysis procedure is proved by comparing the average upper story displacements yielded in each type of analysis, with the average of the upper story displacement of the totality of NTHA-s. In Figure 3 specific displacement demands yielded by the proposed procedure, for each of the 8 accelerograms are represented along with the mean values of NTHA. All the target displacements determined on the capacity curves (Opensees, Seismostruct, and Nefcad) with uniform LLD underestimate the values yielded by the NTHA. The most efficient calculation models in predicting the NTHA upper story displacements for the two sets of accelerograms (0.12g; 0.24g) were proven to be Nefcad with 1st mode LLD (average errors of 13.70%; 16.11%), followed by Seismostruct with DAP adaptive LLD (21,61%;19.87%) and Opensees with DAP adaptive LLD (29.91%; 23.52%).

3.2. Story drift profiles

In order to exclude the influence of the target displacement on the magnitude of the interstory drifts, story drift profiles were compared at two stages, for all analyses at a total drift of 0.82% and 1.10% with respect to the total height H of the structure. Story drift profiles obtained from the pushover analyses conducted with Seismostruct and proposed advanced analysis Nefcad for various LLD were compared in Figure 4 to story drift profiles determined in [9] form pushover analyses and Incremental Dynamic Analyses.

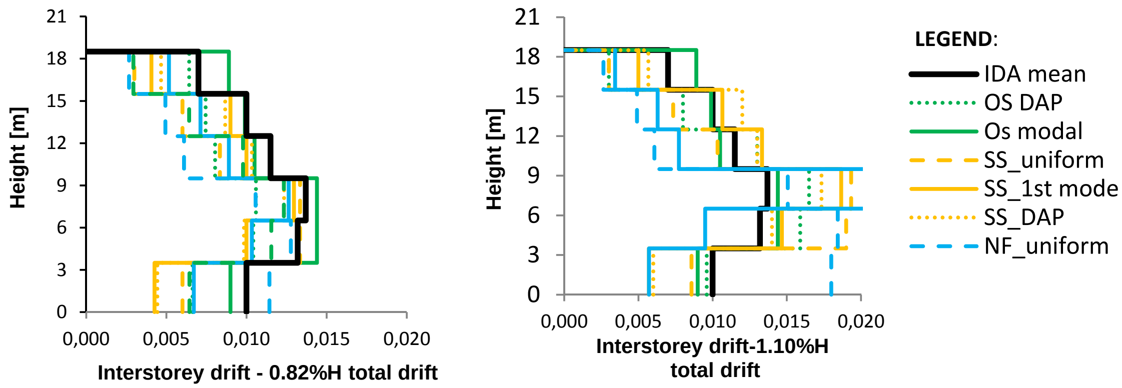

Fig.4.Story drift profile for proposed method and different types of analysis and of the reference Incremental Dynamic Analysis.

4. Conclusions

An integrated method for advanced pushover analysis and seismic performance assessment of 2D reinforced concrete frameworks was presented and validated. The pushover analyses were conducted in Seismostruct and proposed Nefcad advanced analysis software and compared to the existing results in Opensees, for various types of lateral load distributions: uniform, 1st mode, and adaptive (DAP). It can be concluded that the lateral force distributions describe better the structure`s behaviour, the results in target displacements are more accurate. For the analysed structure there weren’t significant differences in the target displacement or story drift profile predictions yielded by the 1st mode and adaptive load patterns, whereas the uniform lateral force distributions induced less accurate results. It is worth noting that both lateral force distribution and the accuracy in modelling of the main sources of nonlinearities exhibited by the RC frame structures, (i.e. material and geometrical) and also the design code-based nonlinear static analysis procedures are extremely important because it influences the predicted lateral strength capacity of the structural system (the abscissa of the pushover curve) and the dissipated energy (area below the pushover curve), which have influence on the strength of the equivalent SDOF system, consequently on the prediction of the inelastic demand.

References

[1] ATC, Applied Technology Council, ATC-40, 1996. Seismic Evaluation and Retrofit of Concrete Buildings, Redwood City, CA

[2] Antoniou S., Pinho R.,2004. Development and verification of a displacement-based adaptive pushover procedures. J. Earthquake Engineering, 8(5): 643–661

[3] Aschheim, M., Black, E.F.,2000. Yield point spectra for seismic design and rehabilitation. Earthquake Spectra, 16(2): 317-336.

[4] CEN, Comite Europeen de Normalisation, EN 1998-1: Eurocode 8, 2004. Design of structures for earthquake resistance; Part 1: General rules, seismic actions and rules for buildings, Brussels

[5] Chopra, A.K.,Goel, R.K., 2002. A modal pushover analysis procedure for estimating seismic demands for buildings. Earthquake Engineering Structural Dynamics, 31: 561–582

[6] Chiorean C.G., 2013. A Computer Method for Nonlinear Inelastic Analysis of 3D composite steel-concrete frameworks. Engineering Structures 57.

[7] Fajfar P., 2000. A Nonlinear Analysis Method for Performance-Based Seismic Design. Earthquake Spectra, 16(3): 573-592

[8] FEMA: Federal Emergency Management Agency, 2005. Improvement of nonlinear static analysis procedures., Washington, DC

[9] Ferracuti, B., Pinho,R., Savoia M., and Francia,R., 2009. Verification of displacement-based adaptive pushover through multi-ground pushover analyses. Engineering Structures, 8(31): 1789-99

[10] Hachem, M.M., BISPEC., 2013. Interactive software for the computation of unidirectional and bidirectional nonlinear earthquake spectra. version 2.20, Help manual. (www.eqsols.com/Pages/Bispec.aspx)

[11] Shakeri, K., Shayanfar,M.A., and Kabeyasawa, T., 2012. A story shear-based adaptive pushover procedure for estimating seismic demands of buildings. Engineering Structures, 32(1)

[12] SeismoSoft, 2014. SeismoStruct – A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures (Help file) (www.seismosoft.com)

[13] Pacific earthquake engineering research center, 2005, OpenSees, Open system for earthquake engineering simulation, PEER Center. Berkeley (USA): University of California

[14] Varga, S., Chiorean C.G., 2015 ”A Computer Method for Advanced Pushover Analysis of Reinforced-Concrete Frameworks”, Proceedings of the Fifteenth International Conference on Civil, Structural and Environmental Engineering Computing, J. Kruis, Y. Tsompanakis and B.H.V. Topping, (Editors).